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UNSTEADY RANS BASED IMPULSE RESPONSE STUDIES OF AGARD WING FOR AEROELASTIC AND FLUTTER ANALYSIS

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ABSTRACT

A study and evaluation of the CFD code IMPRANS developed by CTFD division of NAL is presented for aeroelastic analysis. The transient response of the AGARD 445.6 wing to a step change in the angle of attack is generated using implicit Reynolds averaged Navier-Stokes solver IMPRANS. The frequency domain characteristics of the wing are derived from the CFD data, and validated against the results of DLM method from NASTRAN software. The work highlights a practical method for generating accurate CFD based unsteady aerodynamics data with significantly reduced computational effort as compared to the other excitations.

Key Words: Unsteady CFD, RANS solver, step input, impulse response, aeroelasticity, flutter

NOMENCLATURE

M	Free stream Mach number
Re	Free stream Reynolds number
Δt	Time step

1. INTRODUCTION

Aircraft design requires the consideration of aeroelastic interactions, and the preclusion of associated instabilities such as divergence, flutter, control reversal and so on. Emphasis on weight minimization has led to lighter but more flexible airframes, necessitating the inclusion of aeroelasticity in the preliminary design loop. Although commercial aeroelastic codes based on linear aerodynamic theories are widely used to design for the subsonic and supersonic regimes, certification procedures demand confirmation of the design assumptions through often intensive flight testing for flutter. Besides, these codes do not cover the transonic regime, nor do they capture nonlinear phenomena such as limit cycle oscillations, buffet, aileron buzz and shock oscillations, since they ignore airfoil geometry and other relevant effects.

The above limitations provide motivation for developing Computational Aeroelasticity tools for the accurate analysis and quantification of fluid-structure interactions. Extensive research and development in this area is in progress, enabled by advances in computational tools and techniques that permit quicker unsteady CFD simulations and the formulation of efficient reduced order models of coupled aeroelastic systems. Although high fidelity CFD codes coupled with structural solvers can provide direct results in terms of aeroelastic time response, such schemes do not easily fit into practical design scenarios on account of the high computational costs. Hence, an alternative approach to harnessing accurate CFD estimates in preliminary aircraft analysis has evolved, wherein the CFD model is "interrogated" with motions corresponding to the natural modes of the structure, and the results are used to establish a linearized database of unsteady aerodynamic coefficients. If the data is cast into Generalized Aerodynamic Force matrices in the frequency domain, it can be directly deployed to generate conventional results such as those from the p-k method of flutter analysis. The initial "brute force" process of exciting the fluid at each (reduced) frequency of interest individually has been replaced by broad band excitation through signals such as Gaussian pulse, step, impulse or random, to be converted into frequency domain airloads via convolution or the FFT. The use of staggered signals to excite the fluid sequentially in each of the structural modes has also been proposed. Several research agencies and design houses have developed, or are in the process of developing, in-house codes to carry out the above tasks, e.g., TRANAIR (Boeing), CFL3D (NASA, Langley), ENSAERO (NASA, Ames), EDGE (Swedish Defence Research Agency) and IMPRANS (NAL, India). Critical and realistic

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evaluations of research codes by the industry are also in progress, e.g., [1].

This paper addresses (1) the development and validation of the IMPRANS code to compute unsteady aerodynamic responses to transient structural motions and (2) the development and validation of a method which converts the unsteady time domain data into the frequency domain. In order to establish the methodology, a 3D case was chosen for study, namely the AGARD wing, for which unsteady pressure results are available from DLM lattice method from NASTRAN computations. Details of the IMPRANS code development are given in Section 2. The CFD simulation and the output data processing is dealt with in Section 3. The results of the present study are presented and discussed in Section 4. This section also covers some of the important issues encountered in the CFD simulation and data processing. The outcome of the present study is summarized in Section 5, and a general methodology usable for unsteady CFD based aeroelastic analysis and flutter prediction of realistic configurations such as the Tejas wing is outlined.

2. IMPRANS CODE

IMPRANS [5, 6] is an implicit RANS code developed in-house for unsteady flows. It is solves unsteady compressible RANS equations in three dimensions in a moving domain. Dual time stepping is used with an implicit finite volume nodal point spatial discretization. Inviscid flux vectors are calculated by using the flow variables at the six neighboring points of hexahedral volume. Turbulence closure is achieved through the algebraic eddy viscosity model of Baldwin and Lomax [7]. For a moving body, the equations are solved in the inertial frame of reference by employing a grid which, while remaining fixed to the body, moves arbitrarily with the body. The code allows for specification of boundary conditions on the wall to account for both displacement and boundary velocity.

3. CFD SIMULATION

For the present study, a transient pitching motion of the AGARD wing about its half chord point at Mach 0.5, Re 2.0e6 was considered. The mean and the first harmonic components of pressure are available for this case from DLM lattice method of NASTRAN. Although the harmonic components may be obtained directly from the impulse response via the Fast Fourier Transform (FFT), specifying the impulse in CFD turned out to be rather tricky and even erroneous. Therefore, the step response was generated in CFD, and the impulse response was obtained in two ways: (1) by differentiating the step response with respect to time and (2) by deconvoluting the step signal out of the step response. Both the methods yielded identical results for the impulse response, which was then subjected to the FFT to obtain the harmonic / frequency domain components of the pressure profile. The entire process is illustrated in the flowchart of Figure 1. The step response route is valid in the absence of strong nonlinearities.

The 3D body conforming C-H type of grid is generated around the AGARD wing by using commercial software GridgenV15 in such a way that the grids are clustered properly near the leading and trailing edges and the tip, where the flow is expected to undergo rapid changes. The grid is nearly orthogonal at the surface, with the first grid line lying at 0.00001c normal to the wing surface and 247, 65 and 75 points are chosen in the chordwise, normal and spanwise directions respectively. The outer grid boundary is located at 30 chords from the wing surface. The AGARD wing surface grid is shown in Figure 2, while the 3D volume grid is plotted in Figure 3 to illustrate the grid topology.

To start with, the CFD code was run in steady mode for zero angle of attack, and the steady converged solution was obtained. With this solution as the initial condition, the code was run in unsteady mode to generate the response to a step change of 0.1 degrees in the angle of attack. A non-dimensional timestep of 0.0025, corresponding to a real timestep of 4.9 µsec, was used. The simulation was carried out for a total of 1500 timesteps in order to obtain a frequency resolution of 10Hz.

4. RESULTS AND DISCUSSION

To study the problem in detail-, it was debated whether a simpler planform with lesser wing sweep could be used in place of the AGARD wing. However, considering that IMPRANS had in the past been successfully used for much more complex shapes such as turbine blades, etc, it was decided that the AGARD wing would be retained and the input deformation shape would be simplified instead. Thus the wing was given a step change in the angle of attack while being pivoted at the midpoint of the root chord. As this could be achieved either by mesh morphing or by rigid rotation of the entire mesh, this approach also allowed the mesh morphing feature to be validated. The mesh morphing feature is required for simulating non-rigid effects such as deformations of a structure in its natural modes. More than ten different simulations were carried out, with changes in various parameters. These runs played an important role in identifying the critical parameters for capturing unsteady effects with transient inputs in IMPRANS.

When the first set of IMPRANS results were processed and compared with those estimated by DLM / NASTRAN, the match was found to be quite poor. Therefore, a time delay of 3000 timesteps (corresponding to ~ 8 cycles at a representative frequency of 10 Hz) was introduced in the CFD simulation. The delay was given after re-starting the unsteady code with the converged steady solution as the initial condition, but before feeding in the transient input. This action was based on an earlier experience of characterizing the NACA64A010 aerofoil [3] with a step change in angle of attack in IMPRANS, wherein the delay had effectively ensured that the unsteady step response did not get contaminated by the transients associated with the steady state convergence process. In fact this was a key parameter that needed to be tuned to get a good match with the wind tunnel results for the aerofoil. However, this did not work in the case of the AGARD wing. Subsequently, various other parameters were tweaked, until a good match was obtained. Of the parameters studied, the CFD timestep was found to be the most important: based on literature, $\Delta t = 0.05$ (non-dimensional) was initially chosen, however a good match with DLM could be obtained only when Δt was reduced to 0.005 (i.e., a tenth of the earlier value). Even then, the imaginary part of unsteady pressure did not match at the leading edge outboard region. CFD predicted the same leading edge trend at root and tip regions, whereas NASTRAN indicated a reversal of sign as one goes from wing-root to wing-tip. The NASTRAN trend is consistent with the physics of the rigid rotation, which causes the root and tip leading edges to translate in opposite directions. By reducing the Δt further to 0.0025, the leading edge trend has also been captured in CFD. Also, the results were found to be influenced by the precision of the input values. The results are equally good with either rigid rotation of the entire CFD mesh or morphing of the mesh to achieve the rotation effect. The match was also seen to be influenced by the precision - single / double - to which the deformation shape is defined. Change of turbulence transition point from leading edge to further aft / introduction of laminar flow did not have any significant effect on the results.

The minimum time length of CFD data required for capturing the flutter characteristics. Zero padding to obtain a frequency resolution of 10 Hz keeping in view the natural frequencies of AGARD modes.

5. CONCLUSION

The traditional aeroelastic design approach relies heavily on panel codes, which are not applicable in the transonic regime, nor do they capture nonlinear phenomena such as limit cycle oscillations, buffet, aileron buzz and shock oscillations. The use of unsteady CFD techniques to model and analyze aeroelastic behavior more accurately is on the rise. In-house Computational Aeroelasticity / Fluid Structure Interaction codes at available / under development at various aircraft companies, and an effort to develop the IMPRANS code along similar lines is in progress at NAL, India. Sample results from the code related to the unsteady response of the AGARD wing has been presented in this paper. A good match between the step response results from DLM lattice NASTRAN and present computations is seen, indicating the ability of the code to capture unsteady aerodynamic phenomena in the subsonic and transonic regime accurately. The methodology used is planned to be applied for the aeroelastic analysis of Tejas wing in future.

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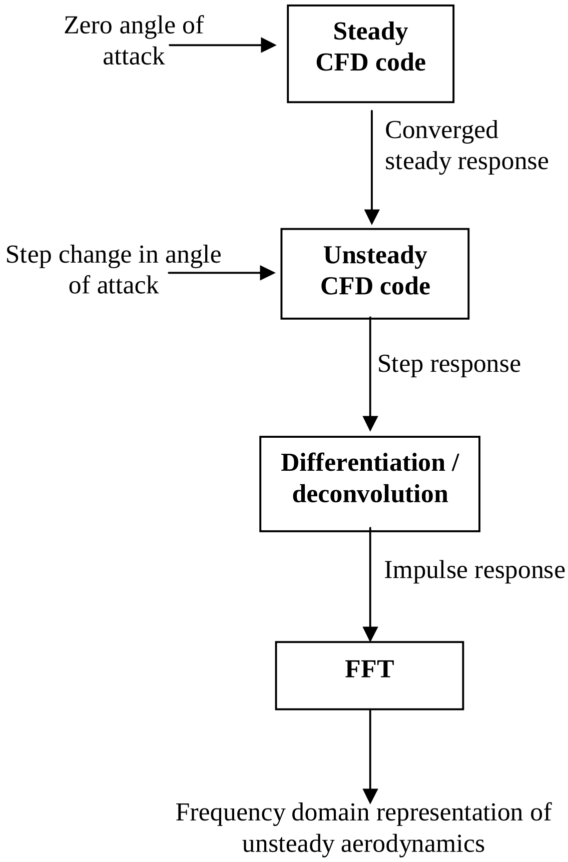

Figure 1. Generation of frequency domain unsteady aerodynamic from CFD

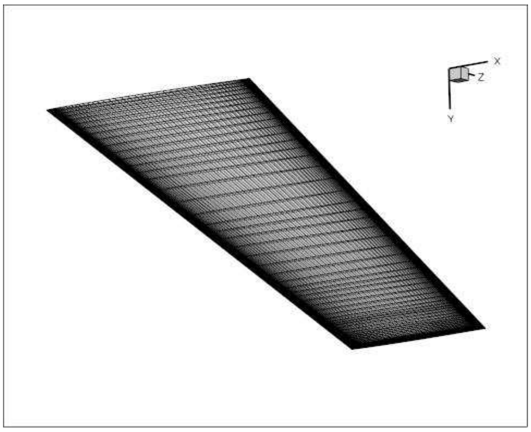

Figure 2. AGARD wing surface grid

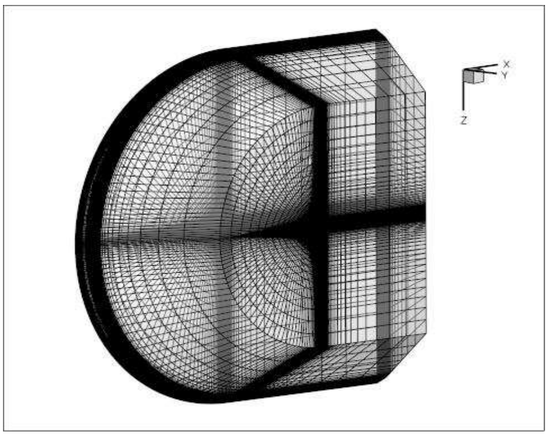

Figure 3. 3D-grid around the AGARD wing

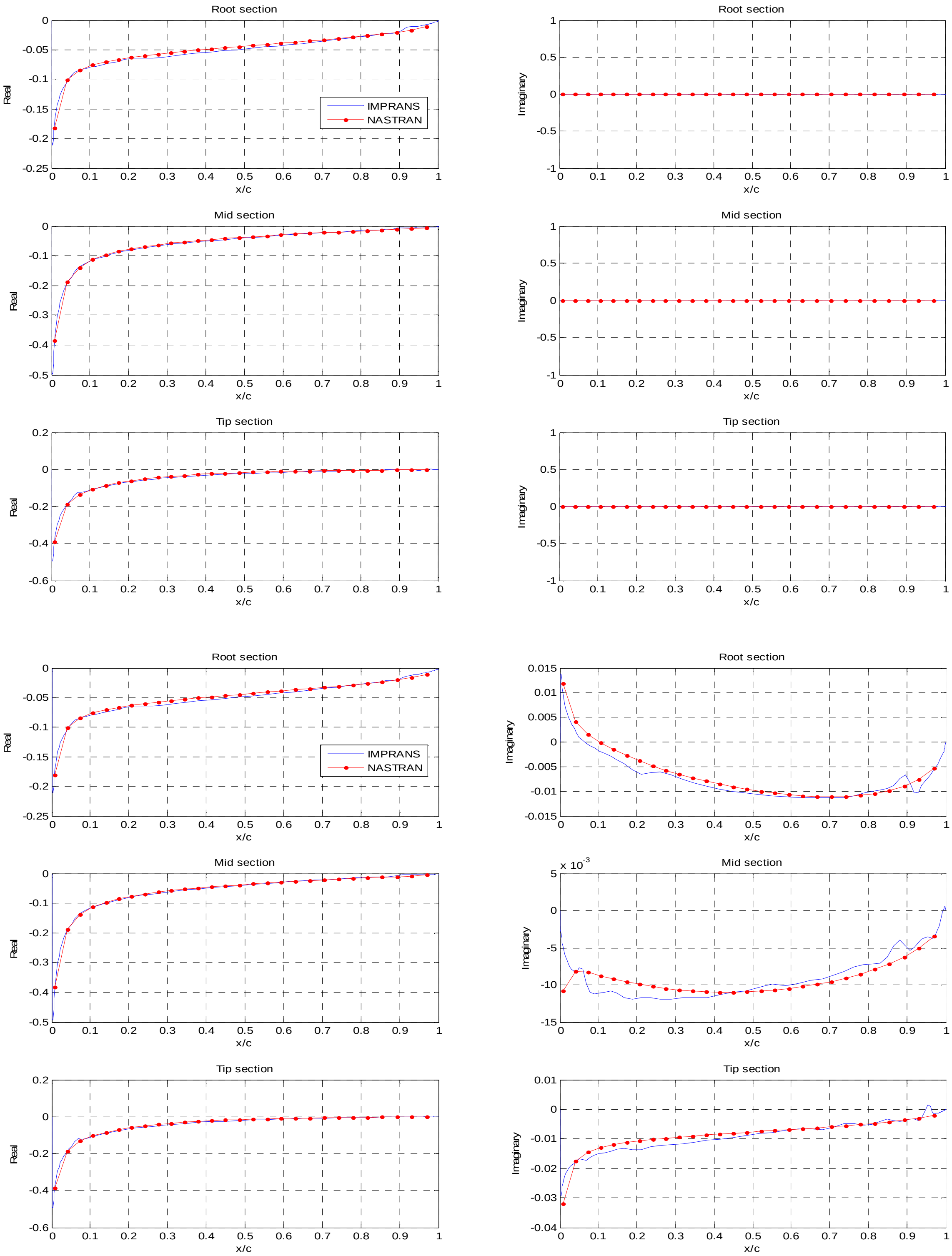

Figure 4. The mean, real and imaginary components of the unsteady surface pressure (Δcp) at 10Hz for rigid pitch about midpoint of root chord for AGARD wing at different span wise section